Water Cherenkov Capabilities

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Introduction

- Where we stand:
  - $\nu_\mu \rightarrow \nu_\tau$ **established**
    - ν_μ disappearance experiments: SK,K2K,Soudan2,MACRO
    - $\sin^2 2\theta_{23}$ and $\Delta m^2_{atm} \sim \Delta m^2_{23}$ measured
  - $\nu_e \rightarrow \nu_x$ **established**
    - ν_e disappearance experiments: Cl,SK,Ga,SNO,KamLAND
    - $\Delta m^2_{12} << \Delta m^2_{23} \sim \Delta m^2_{13}$
  - If $\Delta m^2_{12} << \Delta m^2_{23} \sim \Delta m^2_{13} = \Delta m^2_{atm}$, then

$$P(\nu_\mu \rightarrow \nu_e) \sim \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2(1.27\Delta m^2_{atm}/E_\nu) + f(\delta_{CP})$$

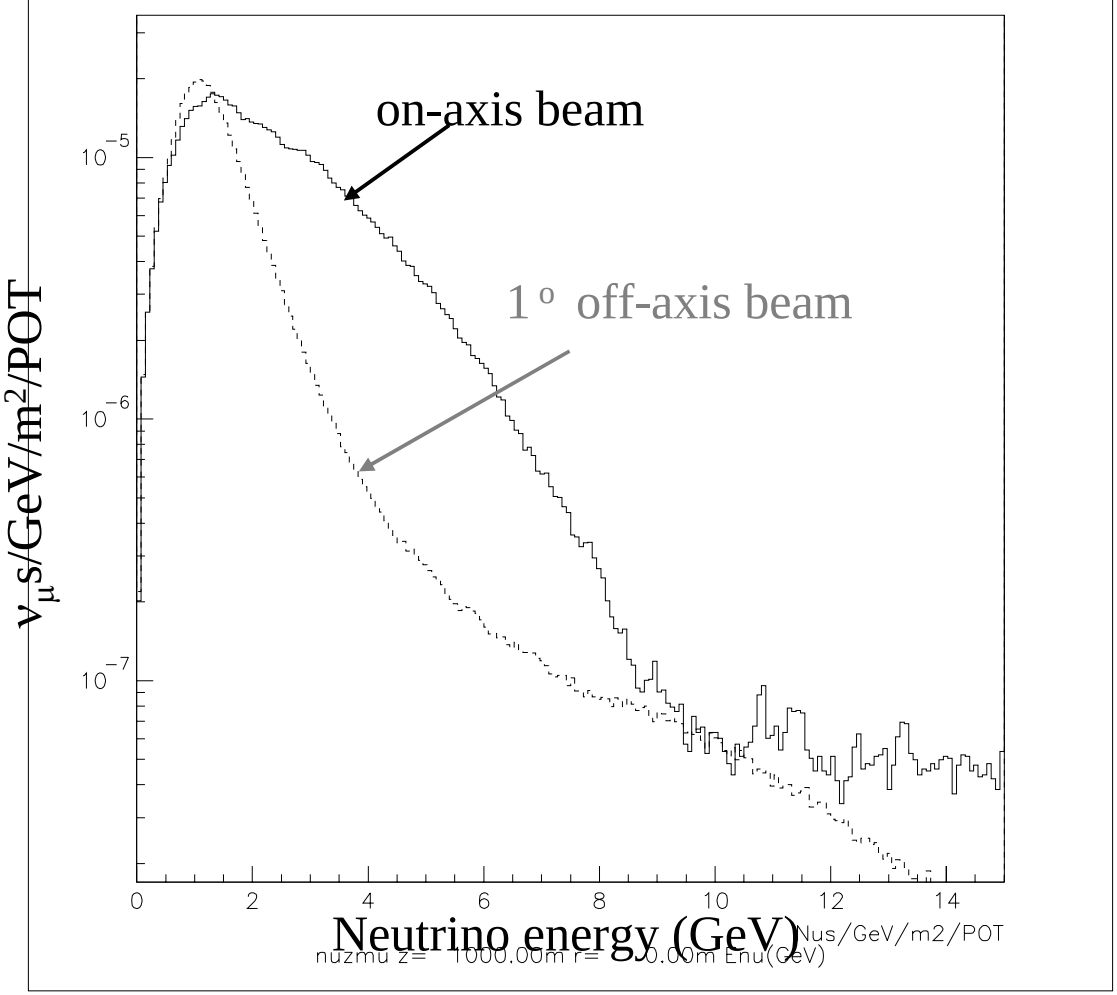
  - Observation of $\nu_\mu \rightarrow \nu_e$ will give us info on $\sin^2\theta_{13}$ and δ_{CP}

- How we do that?
  - **ν_μ –>ν_e and ν_e+N-> e + N' + (invisible πs)**
  - **Look for single electron events**
  - **Major background**
    - ν_μ + N -> ν_μ + N' + π^0 + (invisible πs)
    - ν_e contamination in beam (typically 0.7%)
  - **With a large water Cherenkov detector such as UNO**
    - Cheaper for a large volume than other technologies
    - Potentially quite capable of removing background

BNL Superbeam

- Spectra of on- and off-axis beams

PRD68 (2003) 12002; private communication w/ M.Diwan



Monte Carlo Event Generation

- Atmospheric neutrino events in SK-> BNL superbeam

  - **All ν interactions available**
  - **SK- I geometry/configuration/PMT coverage**
  - **Standard SK-I analysis package** + Special π^0 finder (ntuples)
  - **Neutrino spectrum reweighted for BNL superbeam using all events**
  - **Total number of events normalized with that expected for BNL using QE events (0.5 Mtons, 5 yr running at 2,540 km)**
  - **$\Delta m^2_{21} = 7.3 \times 10^{-5}$ eV^2, $\Delta m^2_{31} = 2.5 \times 10^{-3}$eV^2**
  - **$\sin^2 2\theta_{ij}(12,23,13) = 0.86/1.0/0.04$, $\delta_{CP} = +45,+135,-45,-135^o$**

Probability tables from Brett Viren of BNL

- Interactions included

For first stage study

- **Mode 1 : QE (CC)** * signal
- **Mode 11-13 : Single π from Δ (CC)**
- **Mode 16 : Coherent π^0 (CC)**
- **Mode 21 : Multi π (1.3<W<2.0 GeV) (CC)**
- **Mode 22 : Single η (CC)**
- **Mode 23 : Single K (CC)**
- **Mode 26 : Deep inelastic (2.0 GeV <W) (CC)**
- **Mode 31-34 : Single π from Δ (NC)** * background (π^0 only)
- **Mode 36 : Coherent π^0 (NC)** * background
- **Mode 41 : Multi π (1.3<W<2.0 GeV) (NC)**
- **Mode 42-43: Single η (NC)**
- **Mode 44-45: Single K (NC)**
- **Mode 46 : Deep inelastic (2.0 GeV <W) (NC)**
- **Mode 51-52: Elastic (NC)**

Selection Criteria I

QE for signal, single pi0 for bkg

- Cut 0:
  - **Fiducial volume cut (200 cm inside from PMTs)**
- Cut 1:
  - **1 ring and e- like**
- Cut 2:
  - **E_{ring} > 100 MeV and no decay electrons**
- Cut 3: (π^0 finder info used)
  - **80 < $m_{\gamma\gamma}$ < 160 MeV/c^2**
  - **E_{vis} > 500 MeV**
  - **$\cos\theta_{ring}$ > 0.5**
  - 2 γ s, E_γ > 150 MeV, $\theta_{\gamma\gamma}$ > 9° –> 2 rings

2 γ s, E_γ > 150 MeV, $\theta_{\gamma\gamma}$ > 9° –> 2 rings

BNL report requirements (PRD68,2003,p12002)

To remove invisible π/μ

invariant mass btwn primary ring and an extra ring found by π^0 finder

BNL report requirements

- π^0 finder
  - **π^0 detection efficiency with standard SK software**
  - **π^0 detection efficiency with π^0 finder**

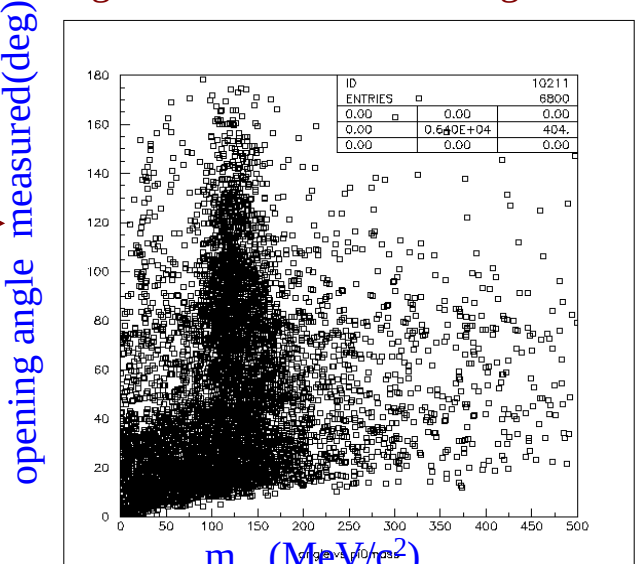
Always finds an extra ring in a single ring event

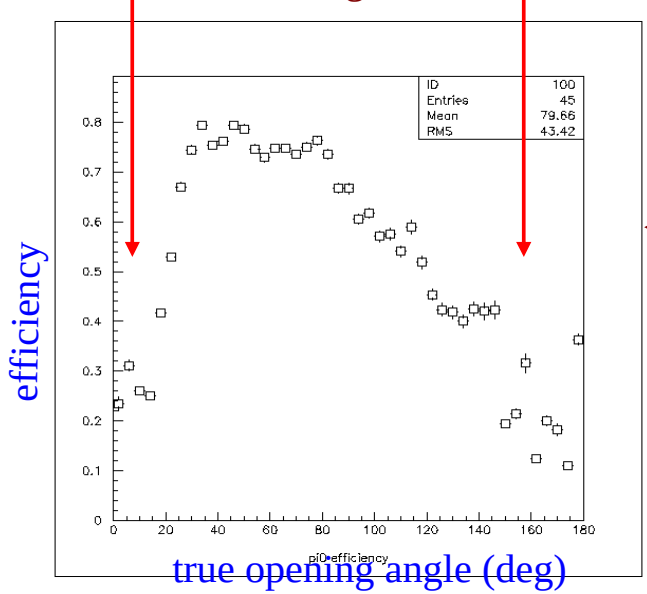
inefficiency overlap

inefficiency weak 2nd ring

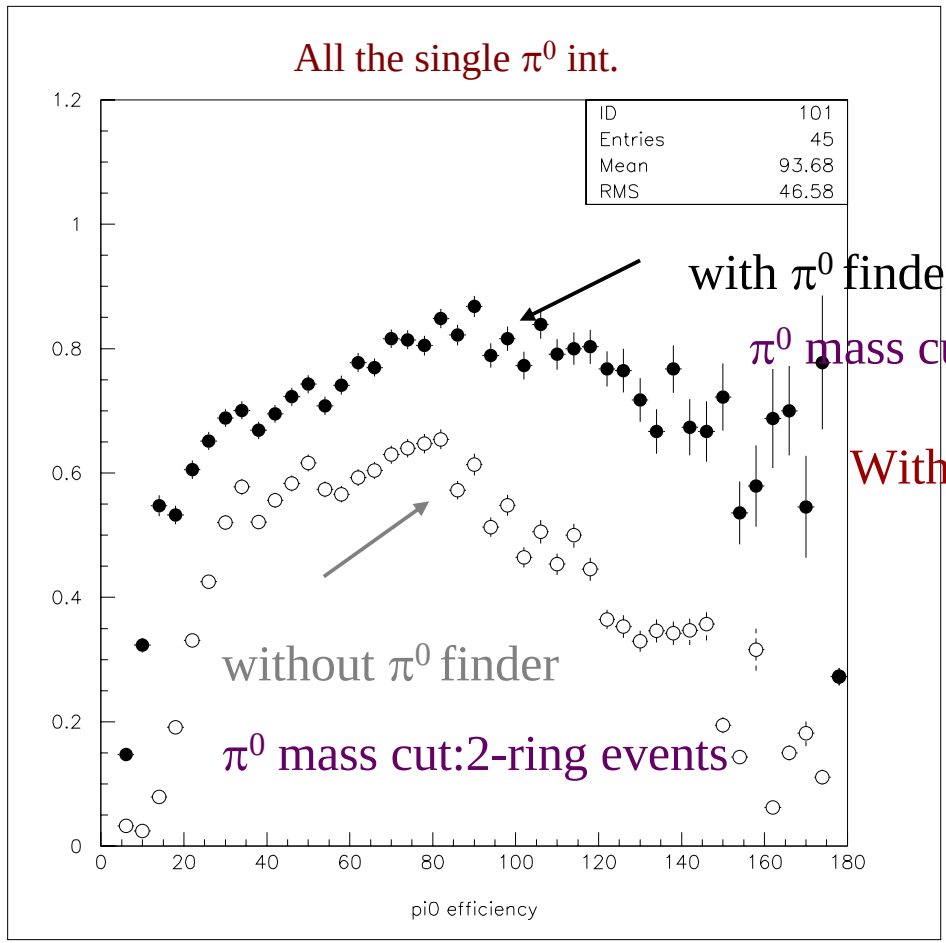
Single e-like events from single π^0 int.

All the single π^0 int.





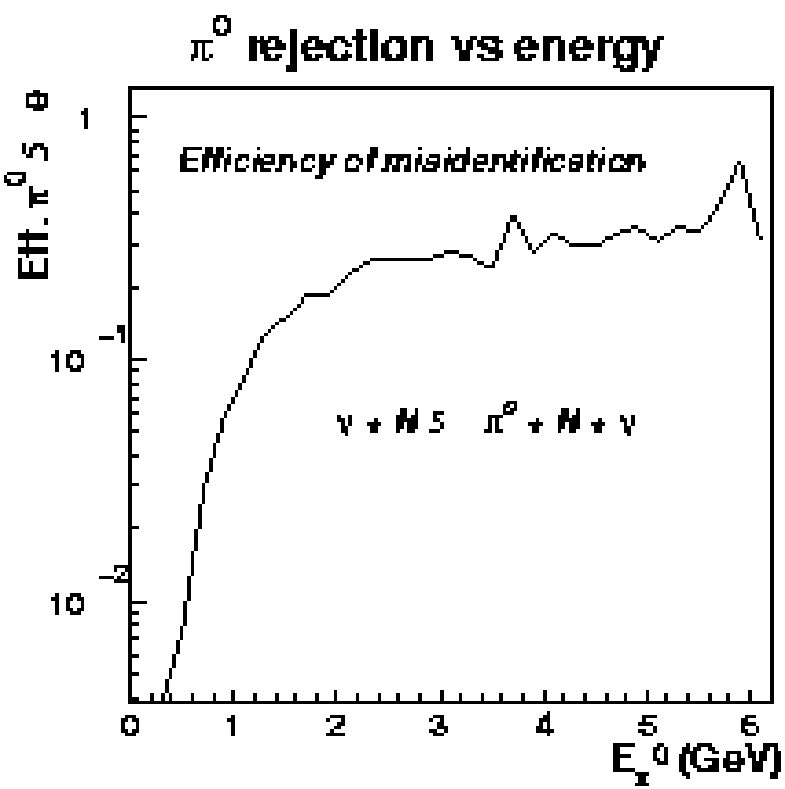
- π^0 finder
  - **π^0 detection efficiency with standard SK + π^0 finder**



Detection Efficiencies and Background Rejection I

- π^0 –> e probability

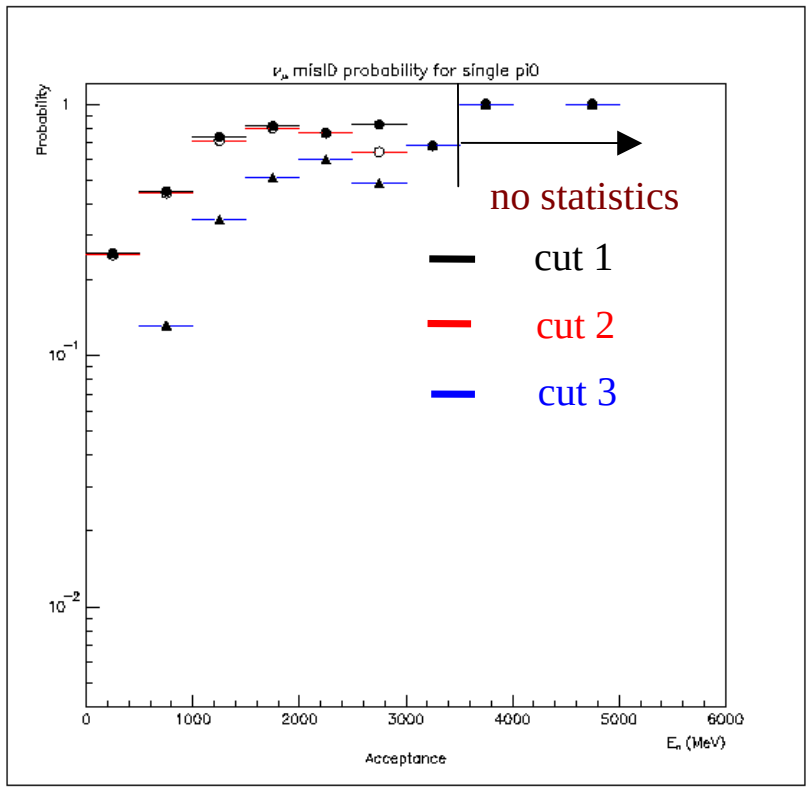
- BNL report



E_π(GeV)

~7.5% at 1 GeV
~20% at 2 GeV

- This study



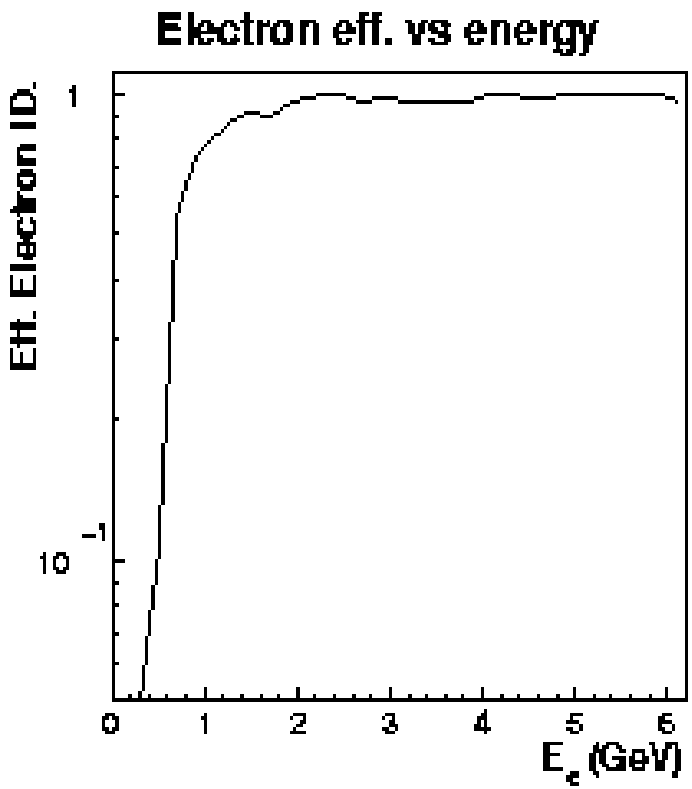
E_π(MeV)

~20% at 1 GeV
~50% at 2 GeV

Detection Efficiencies and Background Rejection I

- ν_e QE efficiency

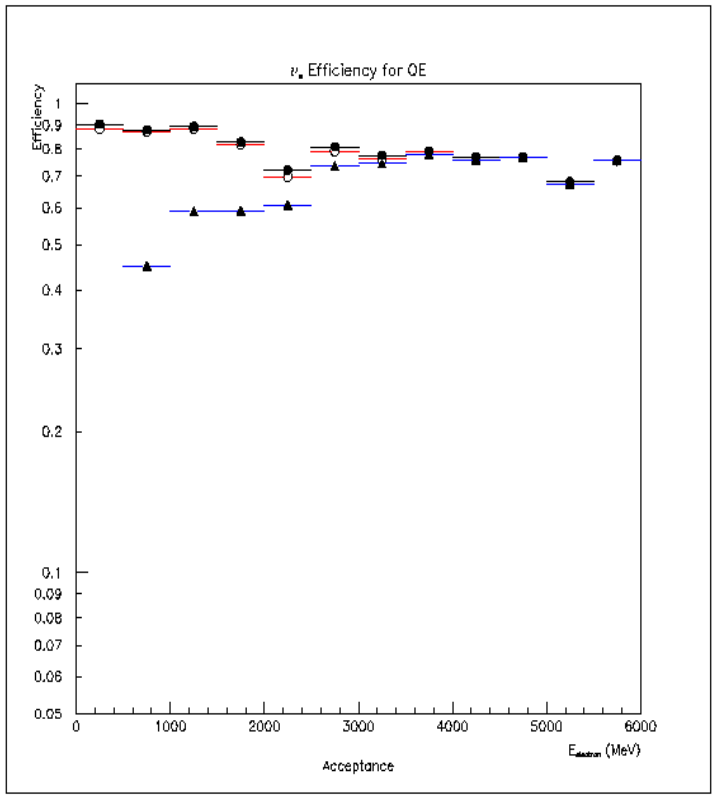
- BNL report



~75% at 1 GeV
~95% at 2 GeV

E_e(GeV)

- This study



~50% at 1 GeV
~60% at 2 GeV

E_e(MeV)

Singnal and Background I

- BNL report

Before any cut

	ν_μ QE	$1\pi^0$
no OSC	13,290	4,238
w/ OSC	6,538	4,238

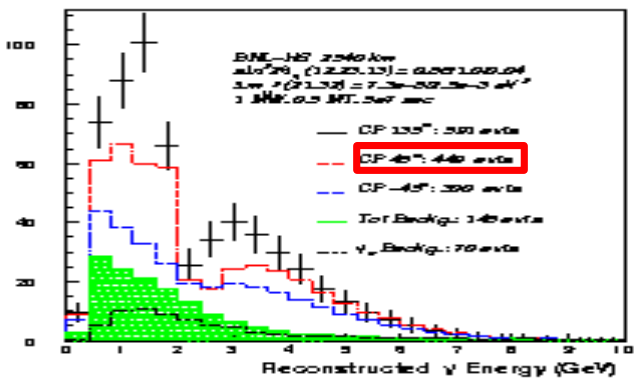
Normalization

- This study

	ν_μ QE	$1\pi^0$
no OSC	13,260	3,628
w/ OSC	6,143	3,628

6% less 14% less

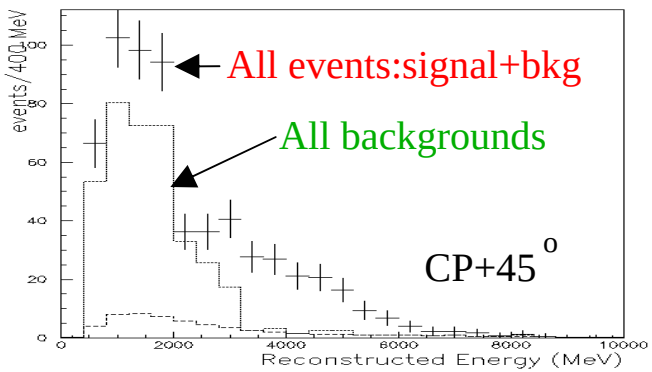
- **Number of signal and background events**



Signal 303 events

All bkgs 146
(76 from π^0)
(70 from ν_e)

CP+45



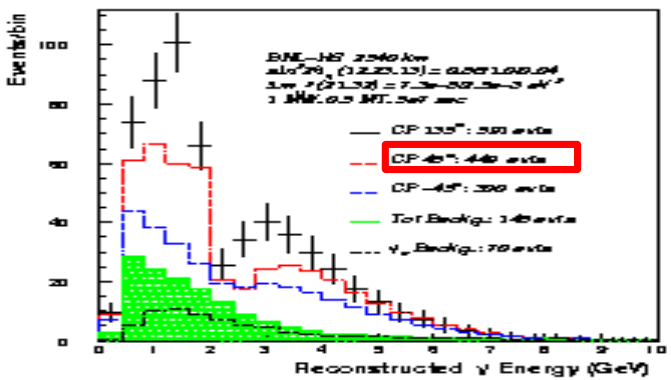
Compare ..... with +

Signal 242 events
(493->412->406->242)

All bkgs 380
(324 from π^0)
(56 from ν_e)

Number of signal and background events

BNL report



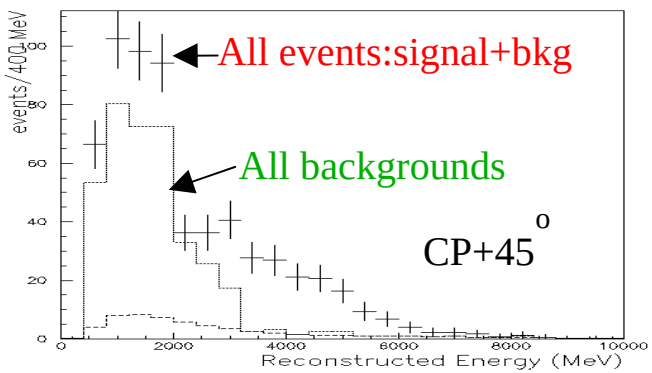
Signal 303 events

All bkgs 146
(76 from π^0)
(70 from ν_e)

Compare

with

This study



Signal 242 events
(493->412->406->242)

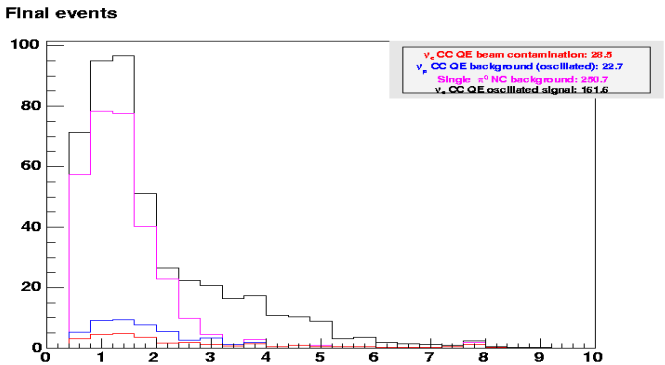
All bkgs 380
(324 from π^0)
(56 from ν_e)

Study by B.Viren

Semi-independent:normalization

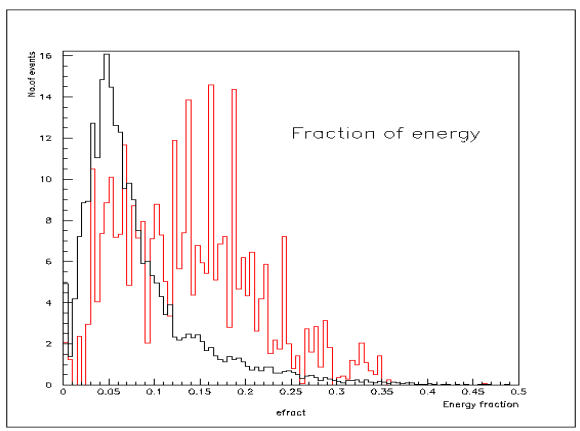
Signal 255 events

All bkgs 308
(292 from π^0)
(30 from ν_e)

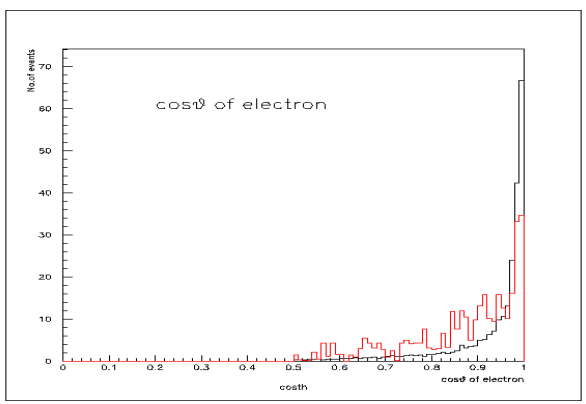


Improvement

- Software – More cuts and better pattern recognition
  - Some possible variables to be used for additional cuts



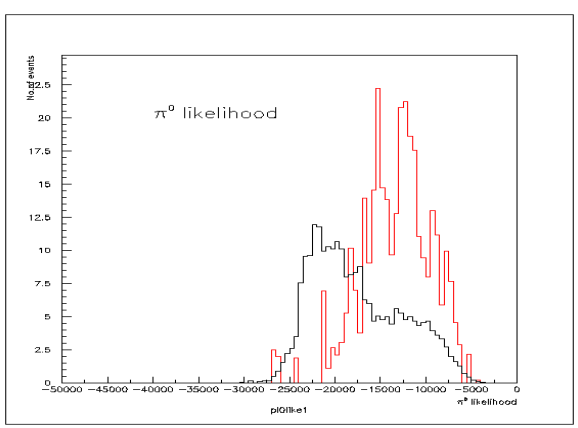
fraction of energy E2/(E1+E2)



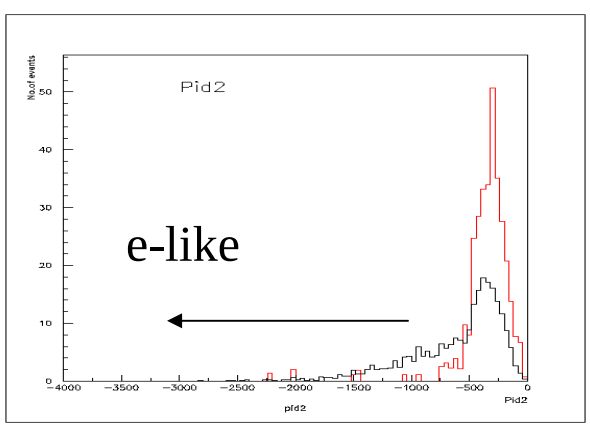
cosθ of 1st ring

Signal : QE

Background:NC π^0



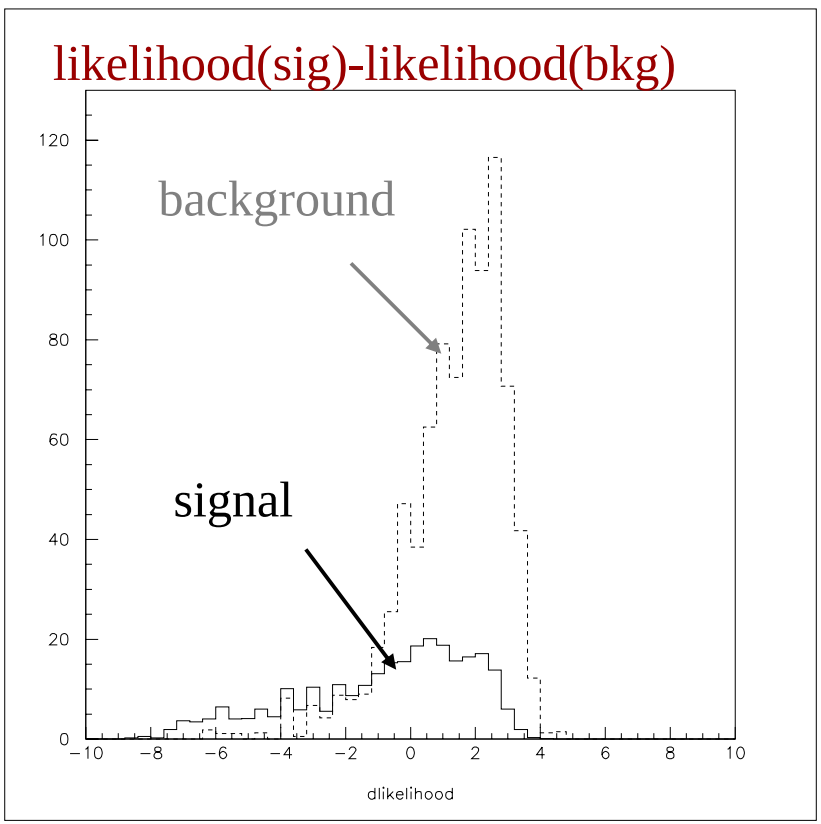
π^0 likelihood

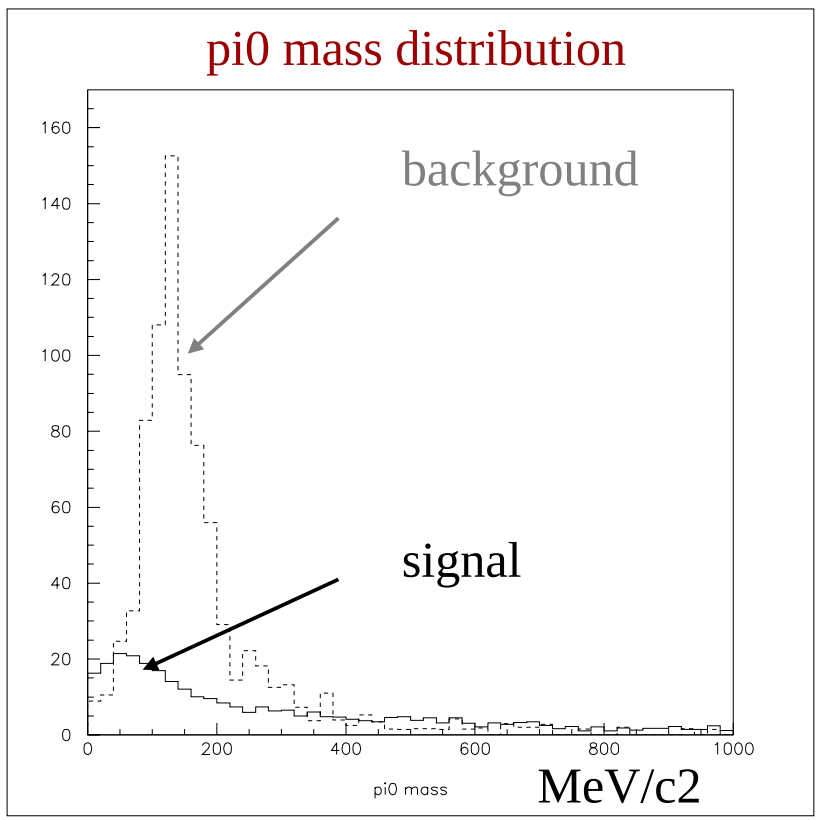


pid (e/mu)

Improvement

- Define likelihood using fraction of 2nd γ energy, cosθ of 1st ring, π^0-likelihood, pid, and π^0 mass . But…
  - Drop cuts on π^0 mass, opening angle, and cosθ





Selection Criteria II

QE for signal, single pi0 for bkg

- Cut 0:
  - **Fiducial volume cut (200 cm inside from PMTs)**
- Cut 1:
  - **1 ring and e- like**

2 γ s, E_γ> 150 MeV, $\theta_{\gamma\gamma}$>9°–> 2 rings

BNL report requirements

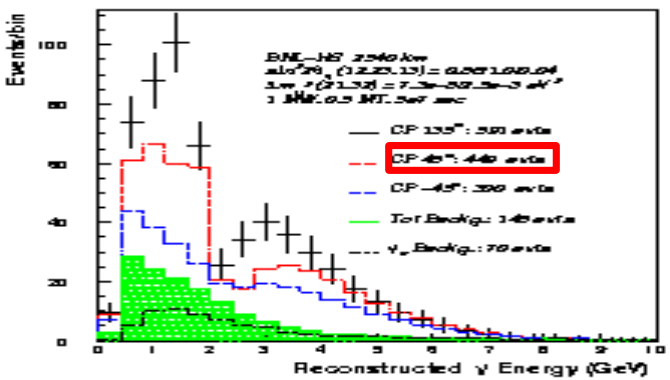
To remove invisible π/μ

- Cut 2:
  - **E_{ring}> 100 MeV and no decay electrons**
- Cut 3:
  - **E_{rec}> 500 MeV** New (Evis->Erec)
  - **Δlikelihood<0.4** New

Singnal and Background II

- BNL report

- **Number of signal and background events**

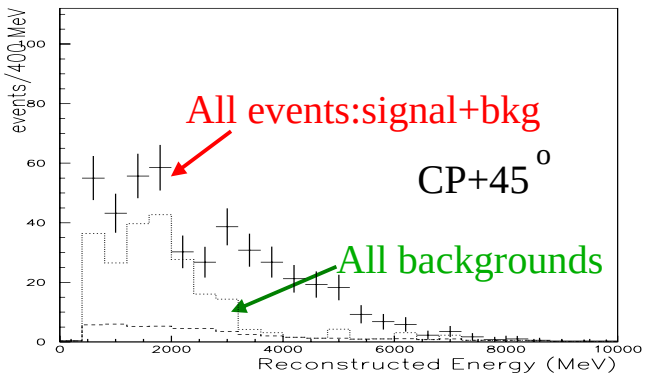


Signal 303 events

All bkgs 146
(76 from π^0)
(70 from ν_e)

- This study

Compare ..... with +

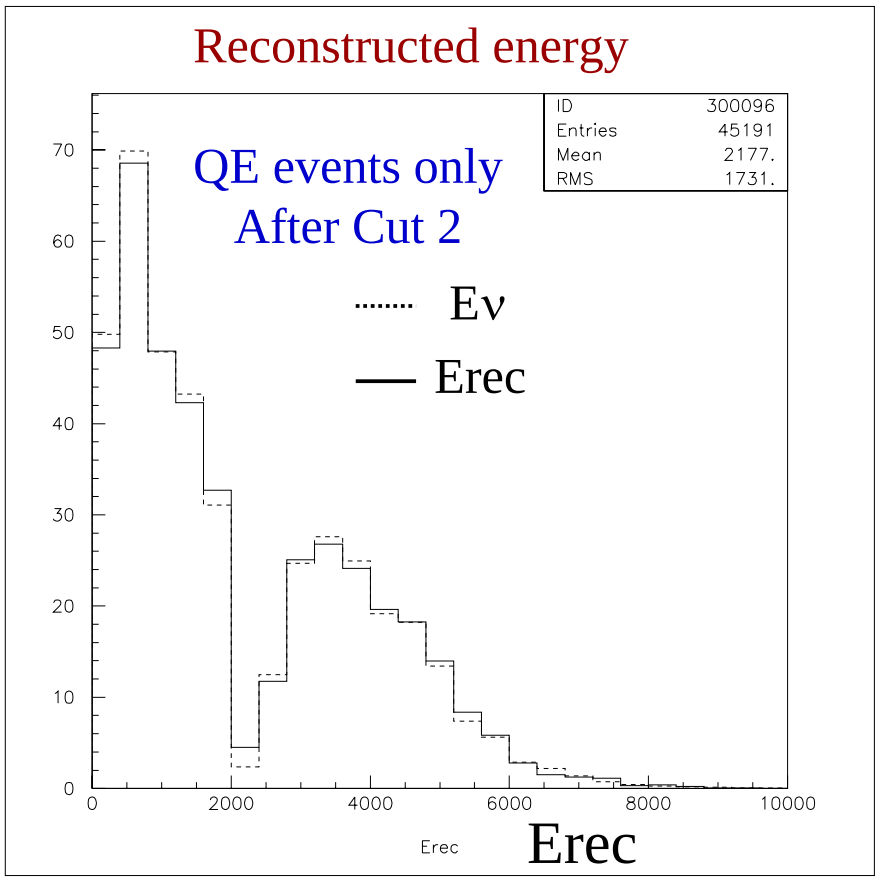


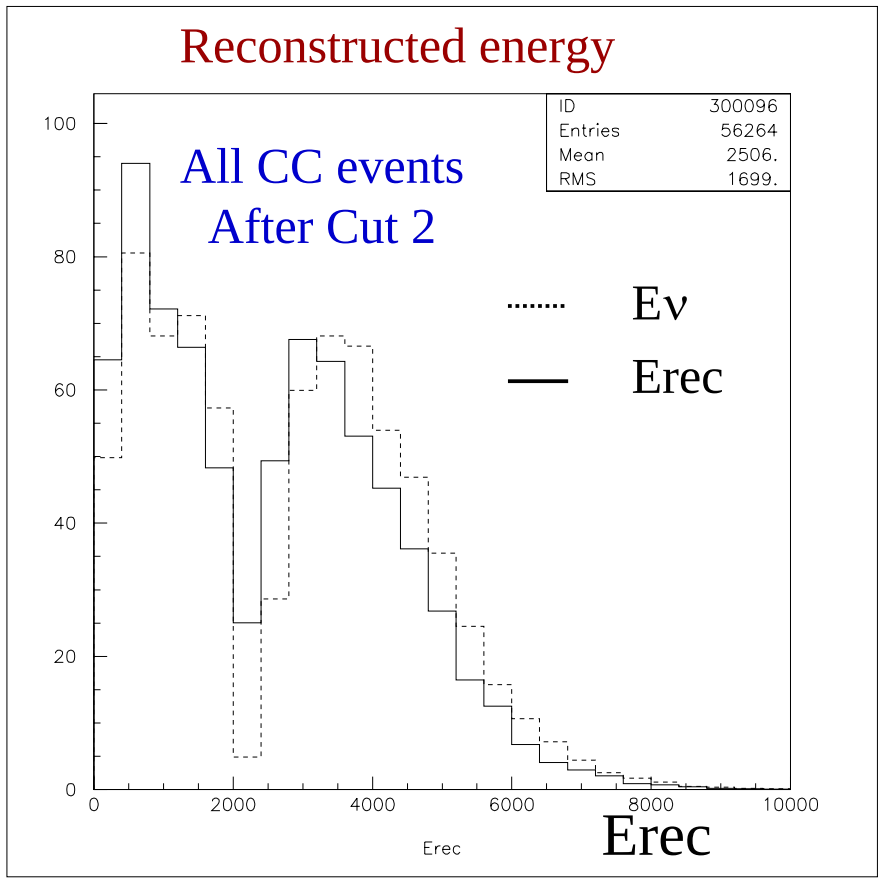
Signal 228 events

All bkgs 233
(180 from π^0)
(53 from ν_e)

What's next?

- **Why don't we turn on all the interactions?**
- **Then what are singals and what are backgrounds?**





Why not accept all CC events as signals?

Selection Criteria III

All ν_e CC for signal, all ν_μ and ν_e NC for bkg

all ν_μ CC for bkg

- Cut 0:
  - **Fiducial volume cut (200 cm inside from PMTs)**
- Cut 1:
  - **1 ring and e- like**
- Cut 2:
  - **E_{ring}> 100 MeV and no decay electrons**
- Cut 3:
  - **E_{rec}> 500 MeV** New
  - **Δlikelihood< to be determined** New

2 γ s, E_γ> 150 MeV, $\theta_{\gamma\gamma}$>9°–> 2 rings

BNL report requirements

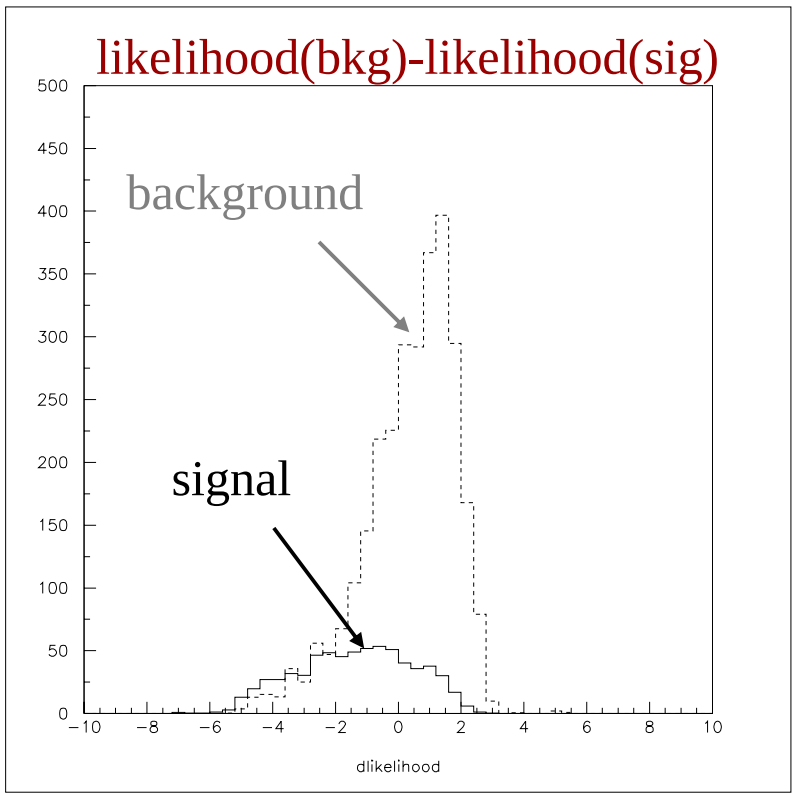
To remove invisible π/μ.

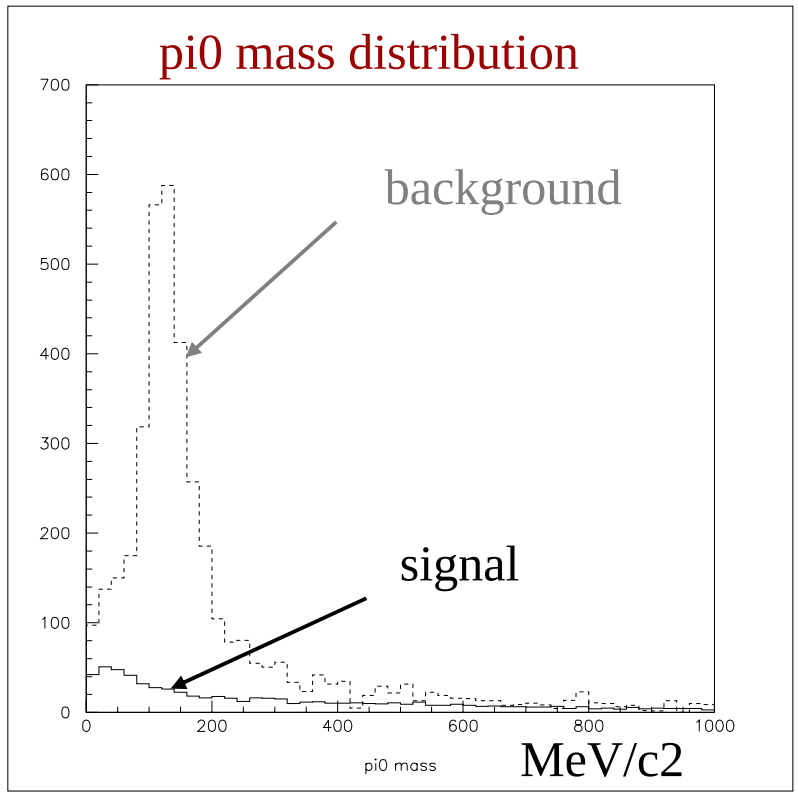
Now this is important to Remove invisible charged Pions.

•Δ likelihood

ln[likelihood(bkg)]-ln[likelihood(sig)]

- Define likelihood using fraction of 2nd γ energy, cosθ of 1st ring, π^0-likelihood, pid, and π^0 mass . But…
  - Drop cuts on π^0 mass, opening angle, and cosθ

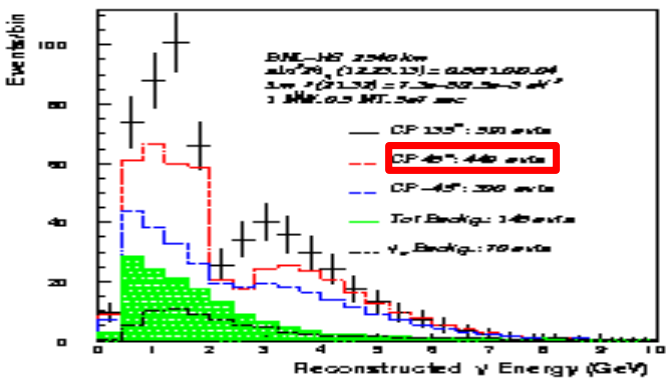




Singnal and Background III

All ν_e CC for signal, all ν_μ and ν_e NC for bkg
all ν_μ CC for bkg

- BNL report
  - **Number of signal and background events**



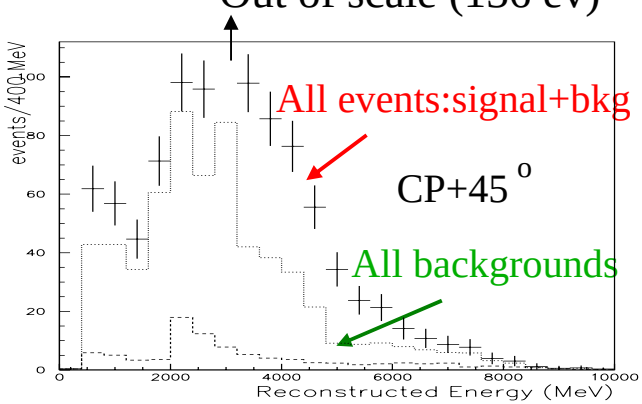
Signal 303 events

All bkgs 146
(76 from π^0)
(70 from ν_e)

- This study

Compare ····· with +

Out of scale (136 ev)



Δlikelihood<-0.8

Signal 397 events

All bkgs 617
(527 from π^0+others)
(90 from ν_e)

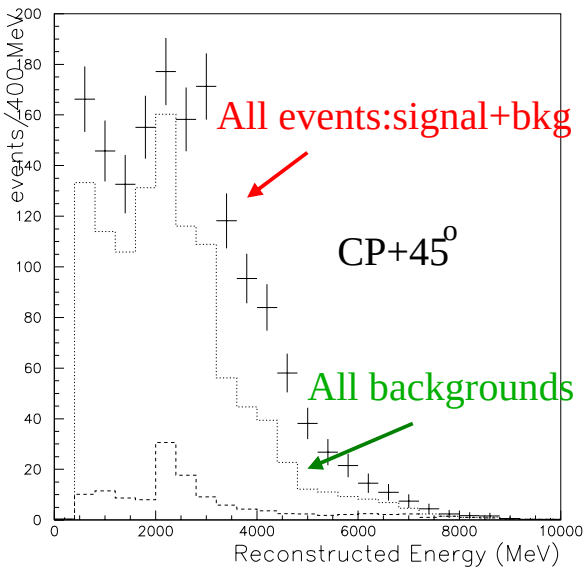
Singnal and Background III

All ν_e CC for signal, all ν_μ and ν_e NC for bkg

all ν_μ CC for bkg

- Effect of cut on likelihood

Δlikelihood< 0.0



Signal 501 events

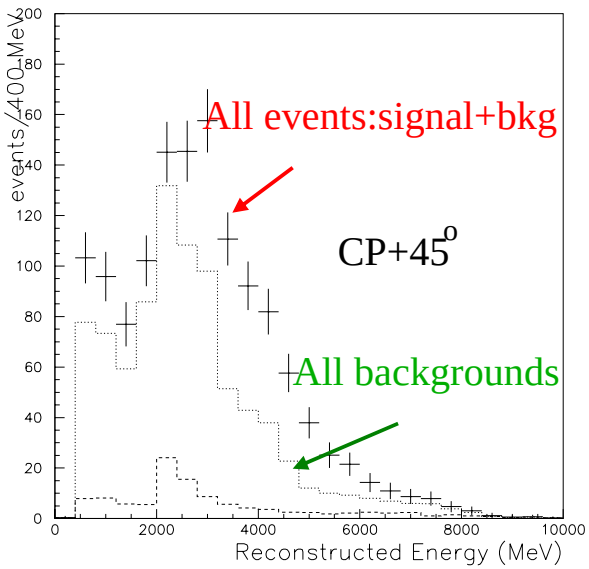
(48% QE events)

All bkgs 1102

(90% NC) (971 from π^0+others)

(131 from ν_e)

Δlikelihood< -0.4



Signal 450 events

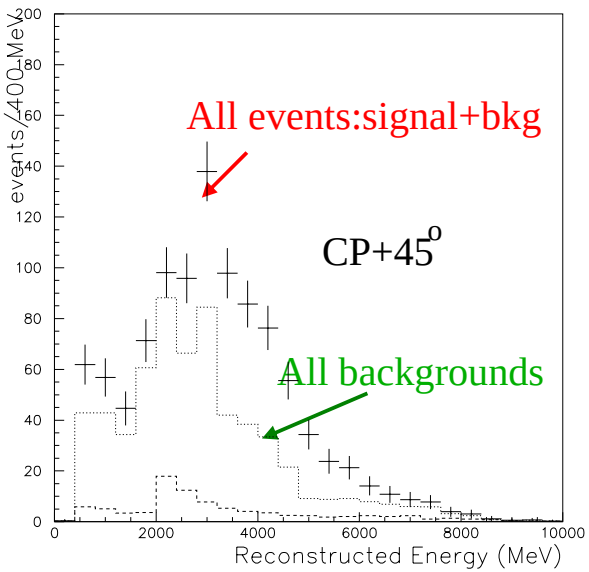
(48% QE events)

All bkgs 853

(89% NC) (743 from π^0+others)

(110 from ν_e)

Δlikelihood< -0.8



Signal 397 events

(48% QE events)

All bkgs 617

(87% NC) (527 from π^0+others)

(90 from ν_e)

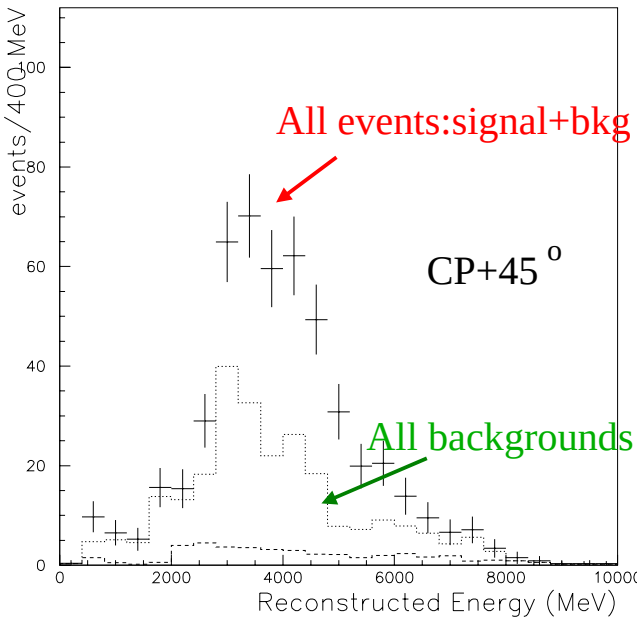
Singnal and Background III

All ν_e CC for signal, all ν_μ and ν_e NC for bkg

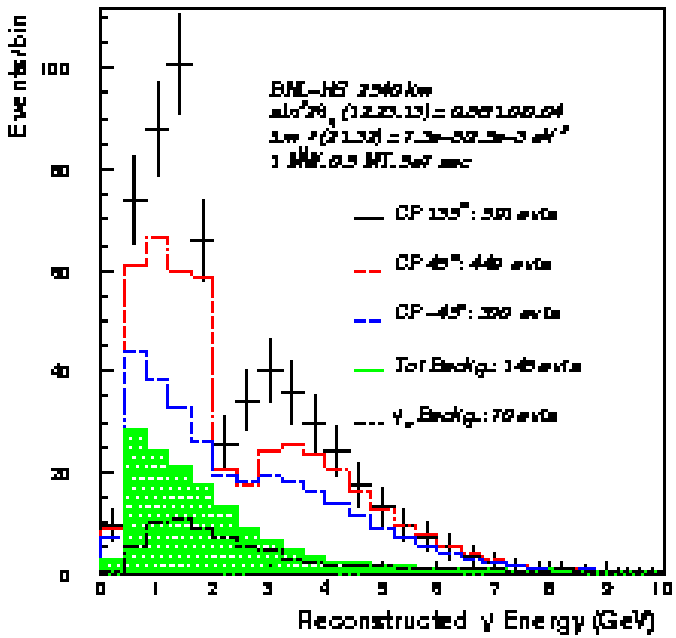
all ν_μ CC for bkg

- Effect of cut on likelihood

Δlikelihood< -2.0



BNL Report



- A tighter cut on likelihood supresses low energy event

- It also modifies energy spectrum very much

- It however improve SN ratio

Signal 251 events

(49% QE events)

All bkgs 253

(86% NC) (210 from π^0+others)

(43 from ν_e)

Signal 303 events

All bkgs 146

(76 from π^0)

(70 from ν_e)

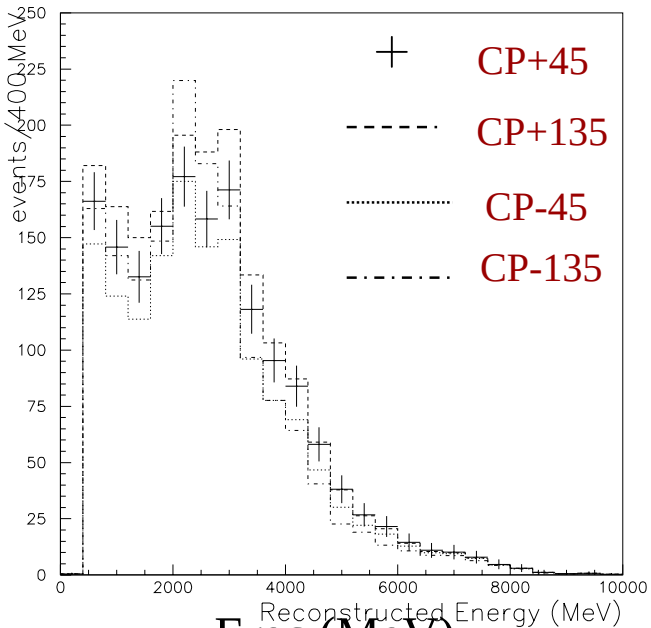
Should we use the tightest cut?

Singnal and Background III

All ν_e CC for signal, all ν_μ and ν_e NC for bkg

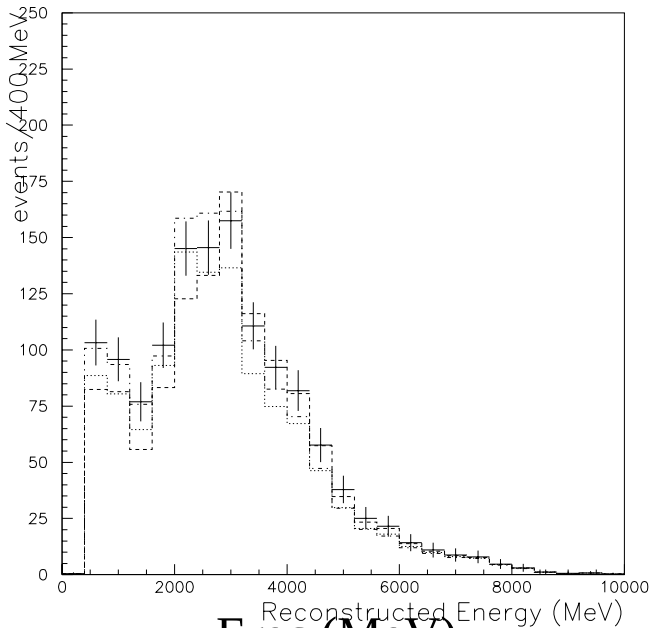
- Effect of cut on likelihood and CPV phase

Δlikelihood< 0.0



Erec (MeV)

Δlikelihood< -0.4



Erec (MeV)

All events:signal+bkg

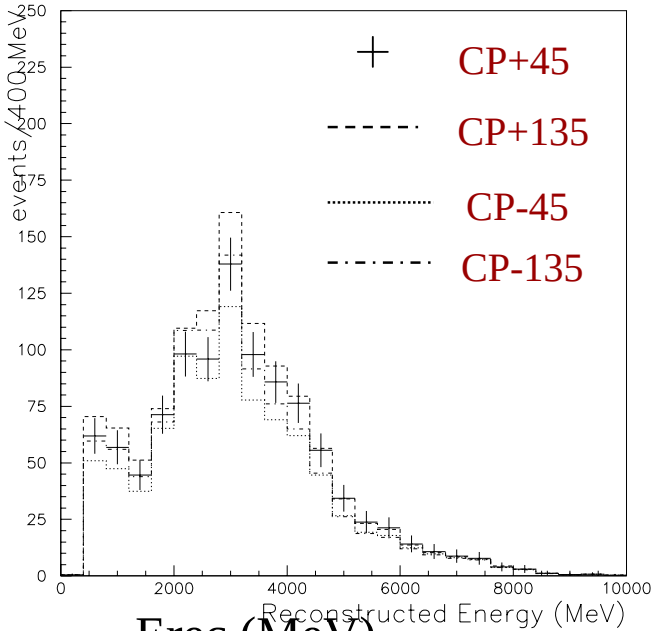
CPV δ (deg)	+45	+135	-45	-135	+45	+135	-45	-135
Signal	501	660	305	464	450	582	281	412
All bkgs	1102	1099	1002	1099	853	853	855	853
π^0+others	971	968	971	968	743	743	745	743
Beam ν_e	131	131	131	131	110	110	110	110

Singnal and Background III

All ν_e CC for signal, all ν_μ and ν_e NC for bkg

- Effect of cut on likelihood and CPV phase

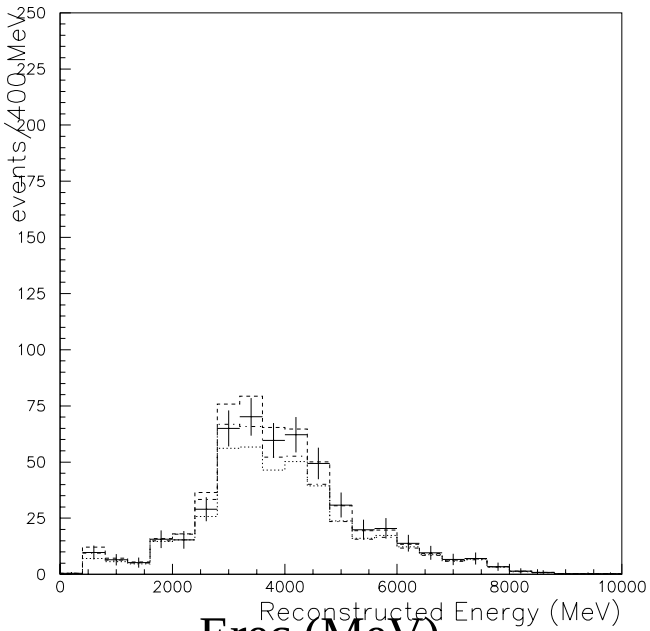
Δlikelihood< -0.8



Erec (MeV)

Δlikelihood< -2.0

All events:signal+bkg



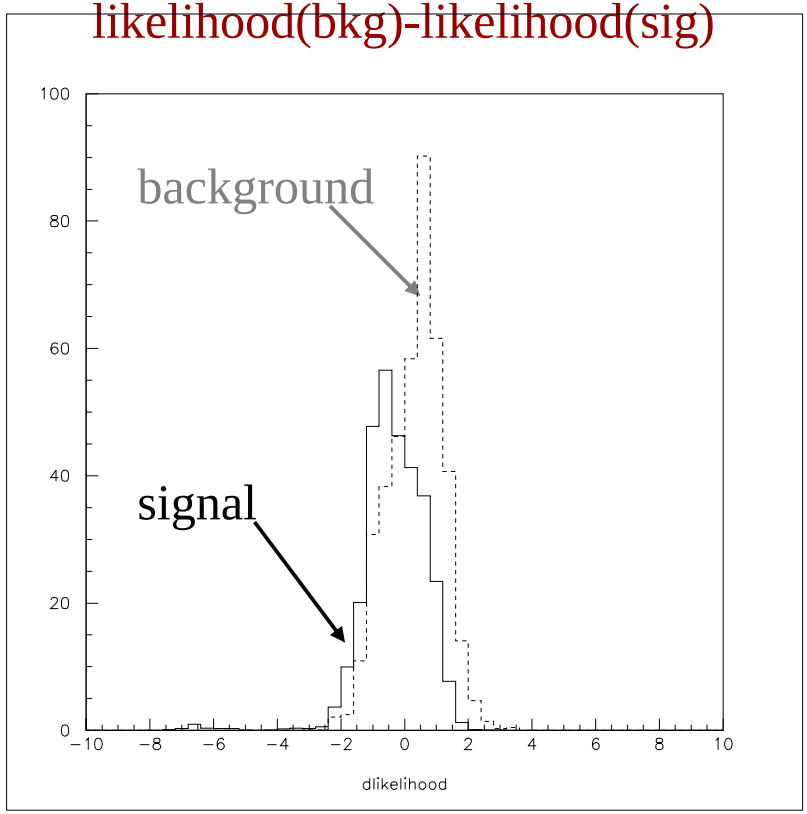
Erec (MeV)

CPV δ (deg)	+45	+135	-45	-135	+45	+135	-45	-135
Signal	397	501	253	357	250	291	167	207
All bkgs	617	615	617	615	253	253	255	253
π^0+others	527	525	527	525	210	209	210	207
Beam ν_e	90	90	90	90	43	43	43	43

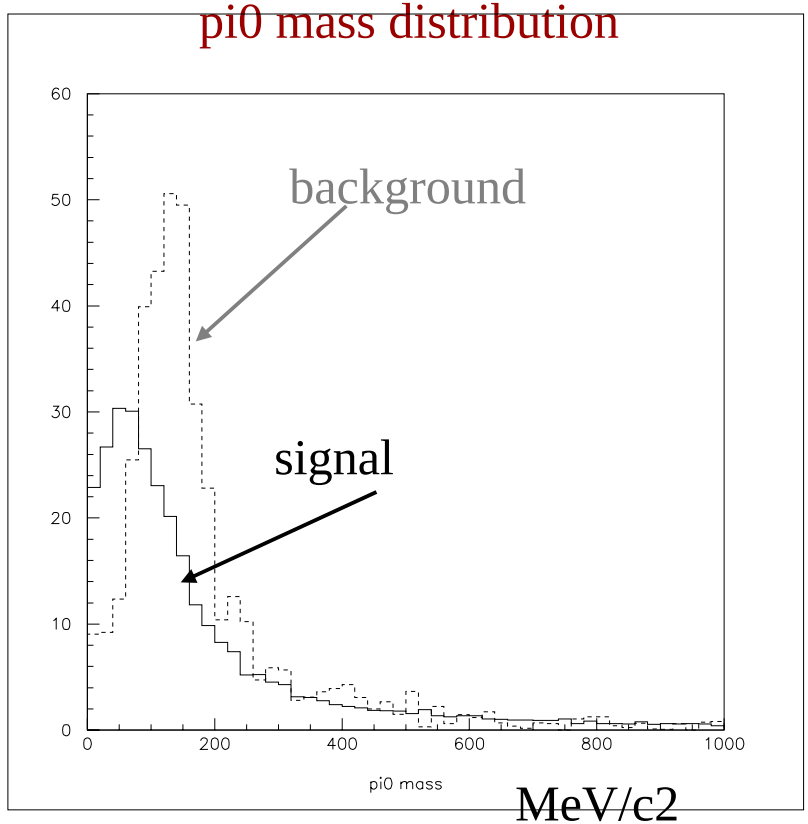
Off-axis beam

- Define likelihood using fraction of 2nd γ energy, cosθ of 1st ring, π^0-likelihood, pid, and π^0 mass as for on-axis beam.
  - Drop cuts on π^0 mass, opening angle, and cosθ

likelihood(bkg)-likelihood(sig)



pi0 mass distribution



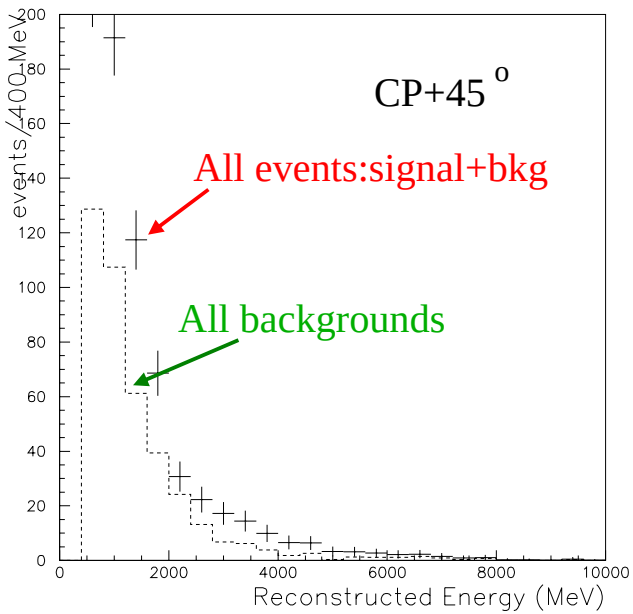
Singnal and Background IV

All ν_e CC for signal, all ν_μ and ν_e NC for bkg

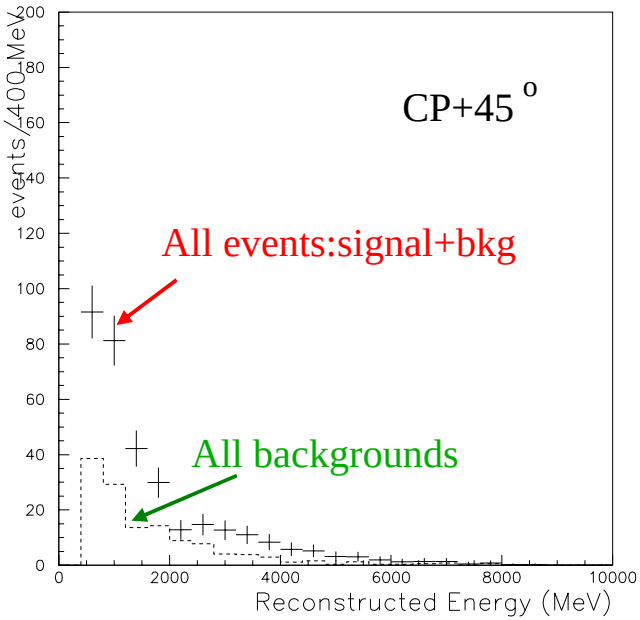
- Effect of cut on likelihood

No contribution from beam ν_e

No Δlikelihood cut



Δlikelihood< 0.0



Signal 310 events

All bkgs 403 + ???

(403 from π^0+others)

(??? from ν_e)

Signal 199 events

All bkgs 131 + ???

(131 from π^0+others)

(??? from ν_e)

Singnal and Background IV

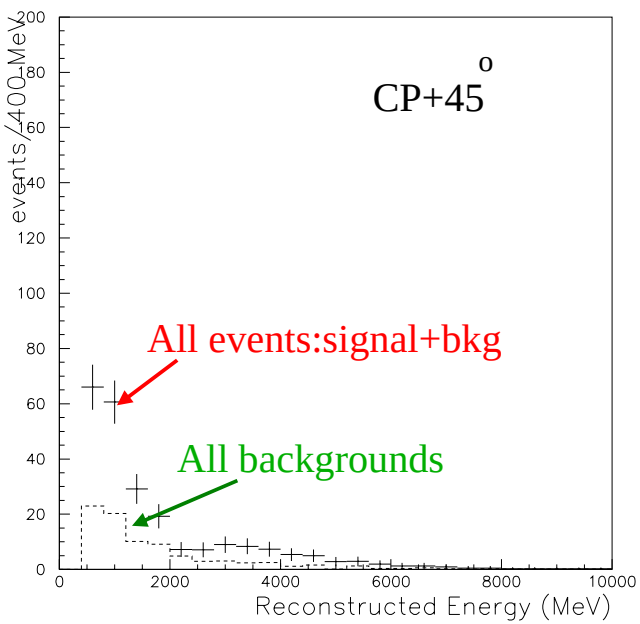
All ν_e CC for signal, all ν_μ and ν_e NC for bkg

all ν_μ CC for bkg

- Effect of cut on likelihood

No contribution from beam ν_e included

Δlikelihood <-0.4



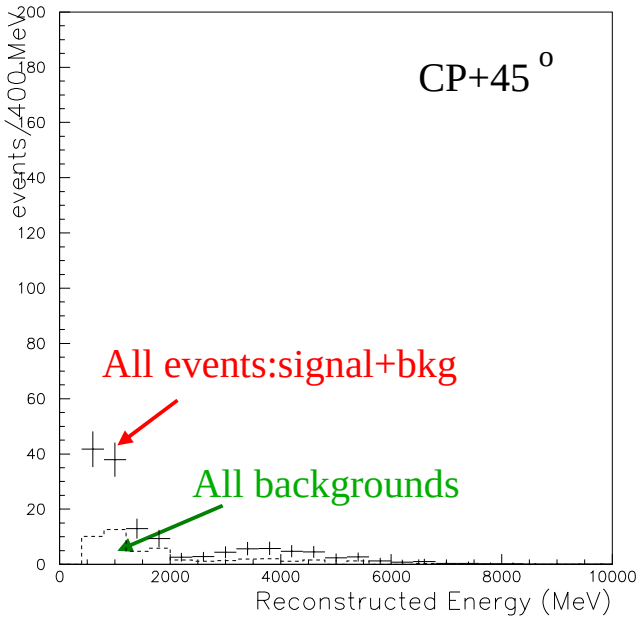
Signal 153 events

All bkgs 85 + ???

(85 from π^0+others)

(??? from ν_e)

Δlikelihood< -0.8



Signal 96 events

All bkgs 46 + ???

(46 from π^0+others)

(??? from ν_e)

Singnal and Background III

All ν_e CC for signal, all ν_μ and ν_e NC for bkg

- Effect of cut on likelihood and CPV phase

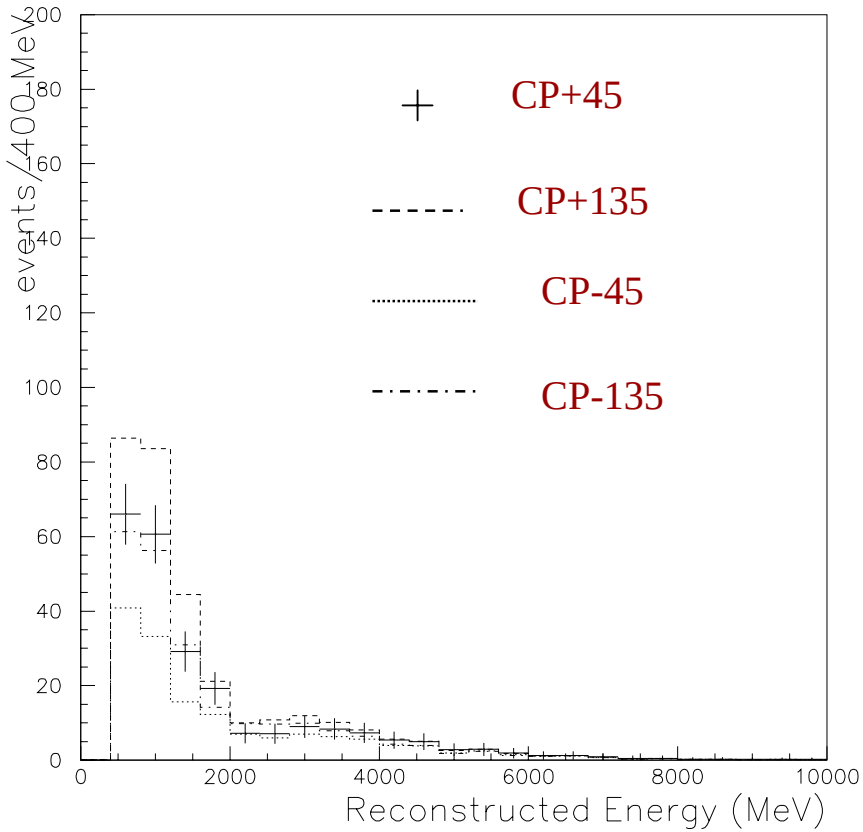
all ν_μ CC for bkg

No contribution from beam ν_e

All events:signal+bkg

CPV δ (deg)	+45	+135	-45	-135
Signal	153	226	62	140
Bkg π^0+others	85	84	85	84

Δlikelihood< -0.4



Erec (MeV)

Conclusions

- Realistic MC simulation study was performed for BNL very long baseline with a water Cherenkov detector
  - Estimates on the signal and background level seem optimistic in the BNL report; This was semi-independently confirmed by Brett Viren of BNL
- It was demonstrated that there is some room to improve SN ratio by reducing the background level while keeping a reasonable signal detection effciency with current available software
  - Further improvement of algorithm/software is essential and possible
  - A larger detector such as UNO has an advantage over a smaller detector such as SK (See C.K. Jung talk)

Conclusions

- The idea of a very long baseline experiment with a large water Cherenkov detector becomes more realistic in terms of physics
  - Further studies are needed